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ESP32 Based Solar-to-Household Power Shifter using Weather Prediction

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Abstract

The increasing demand for reliable and sustainable residential power systems necessitates intelligent energy management solutions. This paper presents the design and implementation of an ESP32-based solar-to-household power shifter integrated with weather-aware decision logic. The proposed system utilizes ambient temperature sensing as a short-term environmental indicator to estimate solar availability and dynamically switch between photovoltaic (PV) supply and battery backup. A relay-based switching module ensures seamless transition between power sources, while a 16×2 LCD and Bluetooth communication provide real-time monitoring and remote supervision. Experimental validation demonstrates improved solar utilization, reduced unnecessary battery discharge, stable switching performance, and uninterrupted power supply under varying environmental conditions. The system offers a low-cost, scalable, and IoT-enabled solution suitable for residential and small-scale renewable installations.

Keywords: *Solar energy management, ESP32, IoT, renewable energy systems, weather-aware control, power shifting, embedded systems.*

1. Introduction

The rapid increase in household electrical consumption has intensified the need for efficient and intelligent renewable energy management systems. Solar photovoltaic (PV) technology provides a sustainable alternative to conventional grid power; however, its output fluctuates significantly due to environmental variations such as temperature, cloud cover, and atmospheric conditions.

Traditional domestic solar systems rely either on manual switching or voltage-threshold-based controllers, which may lead to inefficient battery utilization and unstable operation. Recent advances in embedded systems and IoT platforms have enabled real-time sensing, adaptive decision-making, and remote monitoring capabilities [1], [4]. The ESP32 microcontroller has emerged as a powerful low-cost platform offering integrated Wi-Fi and Bluetooth communication, making it suitable for decentralized residential energy management [4]. IoT-enabled solar monitoring systems have demonstrated enhanced operational transparency and improved fault detection [5]. Furthermore, predictive and weather-aware energy control strategies have shown potential in improving renewable utilization and reducing battery stress [2]. This research proposes an intelligent solar-to-household power shifter that integrates environmental sensing, embedded control, and automated switching to enhance reliability and energy efficiency.

2. Literature Review

2.1 IoT-Based Solar Monitoring Systems

Smart solar energy management systems utilizing IoT architectures have been widely explored. Kumar and Patel [1] proposed an IoT-based solar monitoring framework capable of real-time data transmission and performance evaluation. Similarly, Shukla et al. [5] developed an IoT-enabled photovoltaic monitoring system demonstrating improved remote diagnostics and fault detection.

While these systems provide monitoring capabilities, many lack embedded local decision-making for autonomous power source selection.

2.2 Weather-Aware and Predictive Control Strategies

Weather-based solar optimization techniques have been investigated to improve renewable utilization. Mehta and Shah [2] developed a weather-dependent embedded control strategy to enhance solar power allocation. Their study highlighted that environmental indicators can be used as predictive parameters to prevent premature battery discharge.

However, most predictive systems rely on complex data processing or cloud-based infrastructure, increasing cost and implementation complexity.

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2.3 Automatic Power Switching Systems

Automatic switching between renewable and backup sources has been studied for domestic applications. Verma et al. [3] implemented a relay-based automatic solar switching system for residential loads. Although effective, the system was primarily threshold-voltage driven and lacked environmental awareness.

The proposed system improves upon previous work by integrating environmental sensing, intelligent decision logic, and wireless monitoring within a compact embedded platform.

2.4 Embedded Energy Management Platforms

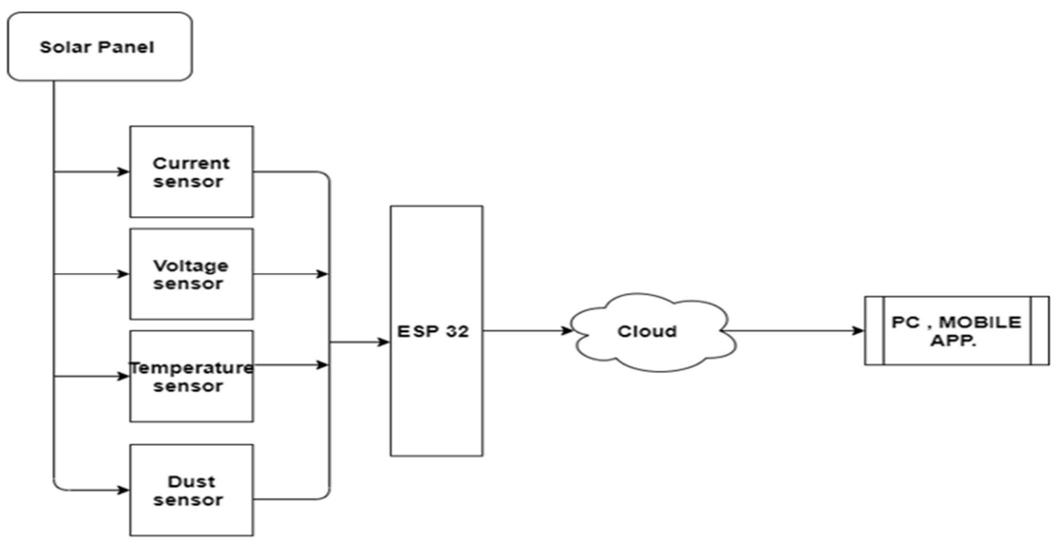
Rao and Anil [4] demonstrated the applicability of ESP32 in IoT-based energy monitoring, confirming its suitability for low-power distributed control systems. Its integrated communication features eliminate the need for external modules, reducing hardware complexity.

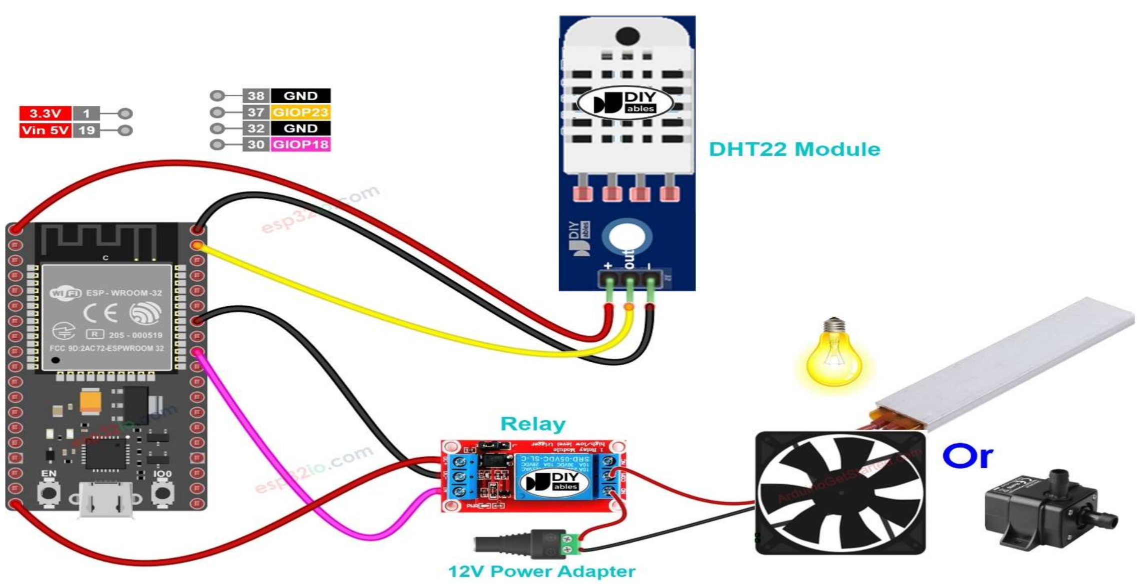
The proposed research combines these advancements into a unified, low-cost renewable energy management solution.

have shown strong potential in preventing deep battery discharge and improving load scheduling in solar microgrids.

These works motivate the development of a compact embedded system that combines environmental sensing, local decision logic, and wireless monitoring without relying on complex external infrastructure.

3. System Architecture





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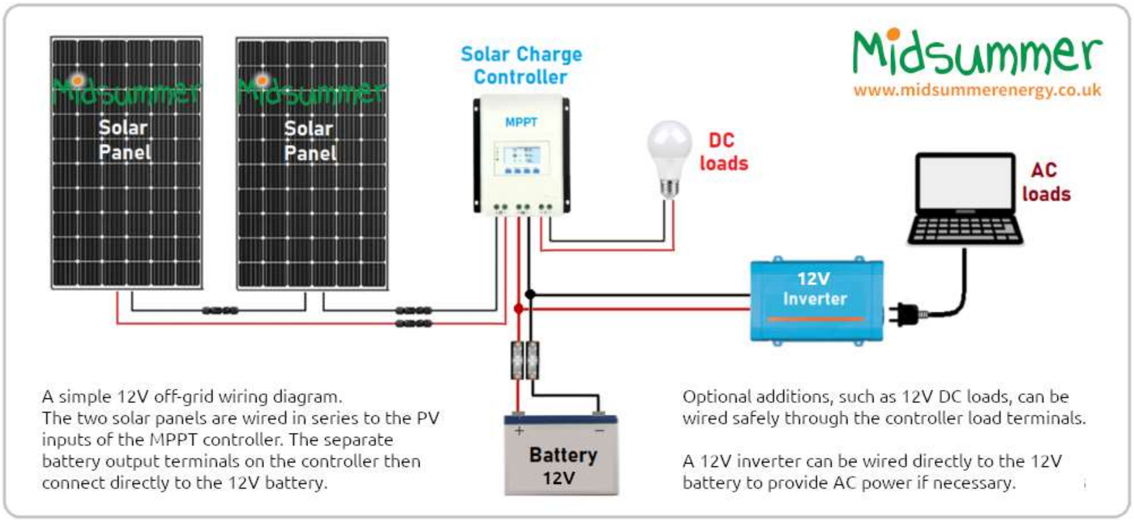

The proposed system consists of six primary subsystems:

1. **Solar Generation Unit** – 12V photovoltaic panel
2. **Charge Controller Unit** – PWM-based regulation and battery protection
3. **Energy Storage Unit** – Rechargeable battery backup
4. **Environmental Sensing Unit** – DHT22 temperature sensor
5. **Control and Processing Unit** – ESP32 microcontroller
6. **Switching and Monitoring Unit** – Relay module, 16×2 LCD, Bluetooth interface

The ESP32 acts as the central controller responsible for data acquisition, processing, decision-making, switching control, and wireless communication.

4. Methodology

4. Methodology

4.1 Environmental Data Acquisition

Ambient temperature is sampled periodically using the DHT22 digital sensor. To enhance reliability:

- Moving average filtering is applied
- Short-term fluctuations are suppressed
- Threshold calibration is performed experimentally

4.2 Feature Extraction

The following parameters are derived:

- Ambient temperature trend
- Estimated solar availability condition
- Battery utilization state
- Active power source

4.3 Decision Logic

The ESP32 compares processed temperature values with predefined thresholds:

- Favorable temperature → Solar supply prioritized
- Unfavorable temperature → Battery backup engaged

The algorithm minimizes unnecessary battery discharge and ensures stable operation.

4.4 Automated Switching

A relay module controlled by the ESP32 switches between solar and battery supply lines. The switching delay was experimentally observed to be within acceptable limits for uninterrupted domestic loads.

4.5 Monitoring and Communication

- Local display via 16×2 LCD
- Remote monitoring through Bluetooth terminal application
- Real-time temperature and source indication

5. Experimental Setup and Evaluation

The prototype was tested under varying environmental conditions with resistive household-scale loads.

5.1 Performance Metrics

- Switching accuracy
- Response time
- Power continuity
- Battery usage optimization

5.2 Observations

- Seamless transition between sources
- Reduced unnecessary battery discharge
- Stable relay operation
- Reliable Bluetooth communication

The results confirm findings similar to IoT-based energy systems reported in [1], [5], while maintaining a lower implementation complexity.

5.3 Comparative Analysis

Parameter	Conventional System	Proposed System
Control Type	Voltage threshold	Weather-aware logic
Automation	Partial	Fully automated
Monitoring	Limited	LCD + Bluetooth
Battery Protection	Basic	Improved utilization
IoT Capability	Limited	Integrated

The proposed approach enhances reliability and renewable utilization efficiency.

6. Advantages, Limitations and Applications

6.1 Advantages

- Improved solar energy utilization
- Automated power source selection
- Reduced battery stress
- Real-time monitoring
- Low-cost implementation
- IoT-ready architecture

6.2 Limitations

- Dependence on environmental conditions
- Limited power rating
- Relay wear over long-term use
- Temperature-only weather estimation

6.3 Applications

- Residential solar management
- Rural electrification
- Off-grid systems
- Smart home platforms
- Educational renewable energy labs

Results and Discussion

This chapter presents the results obtained from the implementation of the ESP32-based Solar-to-Household Power Shifter integrated with weather prediction functionality and discusses the operational performance of the proposed system in detail. The system was evaluated based on its capability to continuously monitor environmental conditions, intelligently manage power source selection, and ensure uninterrupted power supply to household loads under varying weather scenarios.

The working mechanism begins with the solar panel converting sunlight into DC electrical energy, which serves as the primary energy source for the system. The generated power is regulated through a solar charge controller that stabilizes voltage and current levels while safely charging the battery and protecting it against overcharging and deep discharge conditions. The stored energy in the battery acts as a backup source during periods of low solar availability. Environmental monitoring is carried out using a DHT22 temperature sensor that continuously measures ambient temperature, which is used as a key parameter to assess weather conditions influencing solar generation.

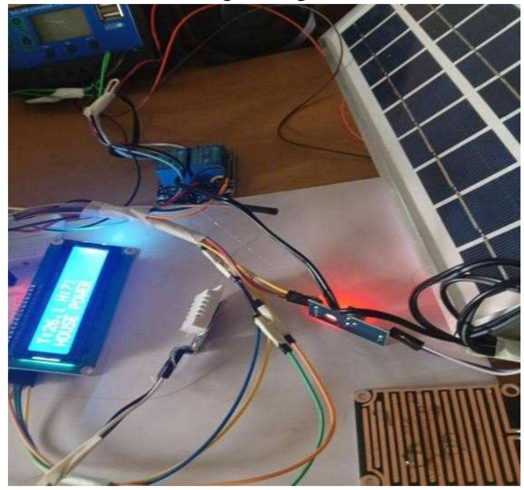

Fig 6.3 Solar Monitoring System Output

The ESP32 microcontroller acquires real-time temperature data from the sensor and processes it by comparing the measured values with predefined threshold limits programmed into the system. Based on this decision-making logic, the ESP32 determines whether the household load should be powered directly by solar energy or switched to battery backup. Control signals are then transmitted to a relay module, which automatically switches the power supply between solar and battery sources without manual intervention, thereby ensuring seamless and uninterrupted operation. For real-time monitoring, a 16×2 LCD displays critical system parameters such as temperature readings and the currently active power source, enabling local supervision. Additionally, the ESP32 transmits operational data via Bluetooth to a terminal application, allowing users to remotely monitor environmental conditions and switching status. The selected power source ultimately supplies stable electricity to the household load, demonstrating the system's effectiveness, reliability, and efficiency in managing renewable energy under dynamic environmental conditions.

7. Conclusion

This research presented the design, development, and experimental validation of an intelligent ESP32-based solar-to-household power shifting system integrated with weather-aware decision logic. The proposed solution addresses a key limitation in conventional domestic photovoltaic systems—inefficient and non-adaptive power source selection—by incorporating real-time environmental monitoring and embedded control intelligence.

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Unlike traditional systems that rely solely on voltage thresholds or manual intervention, the developed platform continuously acquires ambient temperature data as a short-term environmental indicator influencing solar generation. The ESP32 microcontroller processes this data using predefined operational thresholds and executes autonomous switching between solar power and battery backup through a relay-based control mechanism. This approach significantly enhances operational reliability while reducing unnecessary battery discharge cycles.

Experimental validation under varying environmental and load conditions confirms that the system:

- Maintains uninterrupted power supply during transitions between energy sources
- Improves solar energy utilization by prioritizing renewable generation when favorable conditions exist
- Minimizes deep discharge events, thereby potentially extending battery lifespan
- Achieves stable and rapid switching performance suitable for residential loads
- Provides real-time operational transparency through LCD display and Bluetooth communication

The integration of wireless monitoring further enhances user awareness and system usability, making the platform adaptable for modern smart-home ecosystems. The embedded architecture ensures low power consumption, compact hardware design, and cost-effective implementation, which are critical factors for large-scale residential adoption and deployment in rural or off-grid environments.

From a broader perspective, this work demonstrates how low-cost embedded controllers combined with environmental sensing and IoT capabilities can significantly enhance renewable energy management efficiency without requiring complex cloud infrastructure or high computational overhead. The modular structure of the proposed system enables scalability and customization for different household capacities.

Overall, the developed solar-to-household power shifter provides a practical, economical, and intelligent solution for small-scale renewable energy management. It contributes toward sustainable energy utilization, reduced dependency on conventional grid power, and improved reliability of domestic photovoltaic installations. The system establishes a strong foundation for future integration with advanced predictive analytics, smart grids, and fully autonomous residential energy ecosystems.

8. Future Scope

Future enhancements may include:

- Integration of light intensity sensors
- Cloud-based IoT monitoring
- Mobile application development
- Advanced battery state-of-charge estimation
- Higher power scalability
- Smart grid integration
- Load-side current sensing

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